CABLE FAILURES AND PROTECTIVE RELAY OPERATION ASSOCIATED WITH NASA GLENN'S 10x10 SUPERSONIC WIND TUNNEL

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Background

During a two-month period, NASA Glenn Research Center in Cleveland, Ohio experienced two failures of high voltage cables associated with its 10 x 10 supersonic wind tunnel (SWT) and a ground problem from the local utility. This paper addresses these problems and associated relay operations.

The following incidents are reviewed:

1. Failure of 6.9kV transformer drive cable and operation of protective relaying.
2. Detection of problem on First Energy's 138kV utility power system with new micro-processor based relays.
3. Failure of 138kV transformer primary cable and operation of protective relaying

All three incidents were associated with transformer *K10*, one of four transformers feeding the 10 x 10 SWT complex. A simplified one-line of transformer *K10* and its high voltage connections appears in Figure 1.

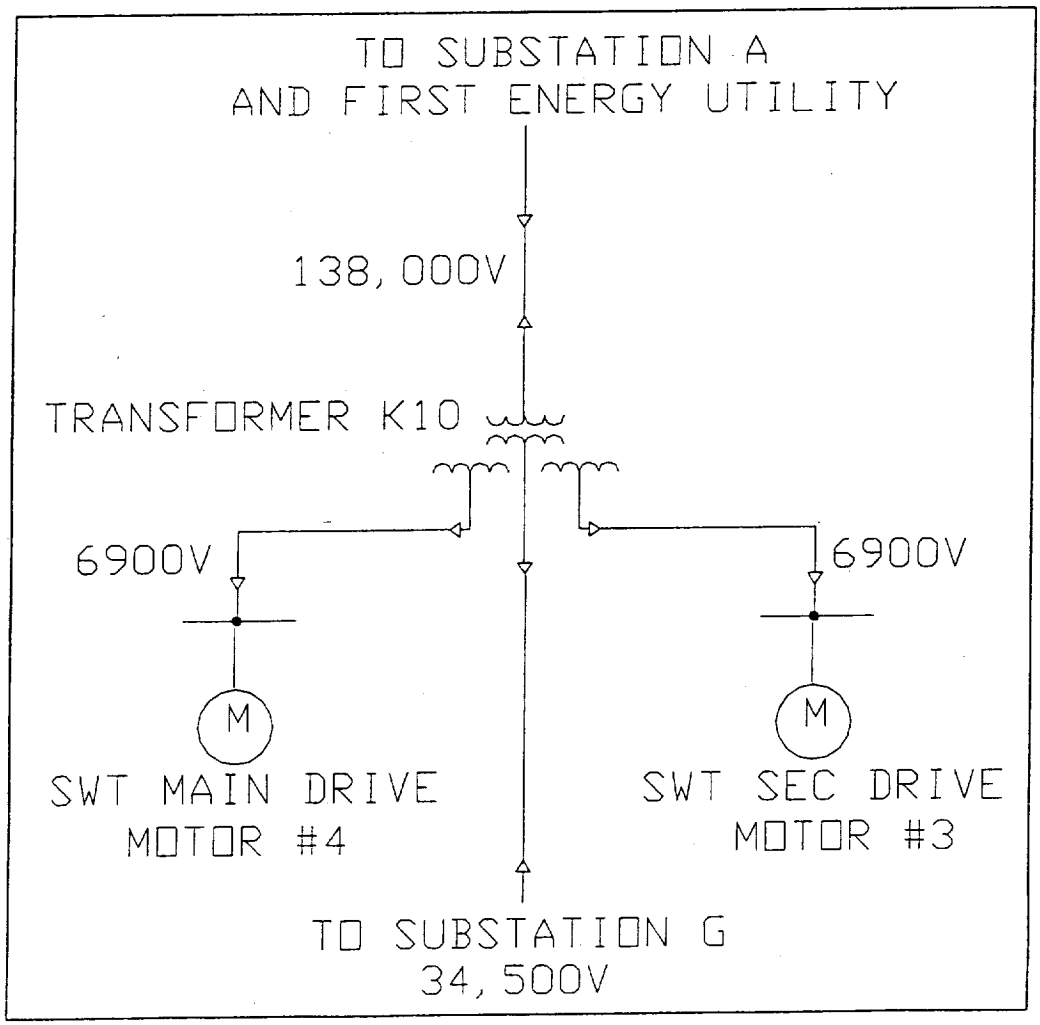

FIGURE 1 – ONE LINE OF XFMR *K10*

FAILURE OF 6.9kV CABLE TO 10 x 10 SWT SECONDARY DRIVE MOTOR #3

On 12/06/2001 Transformer *K10* tripped off line. Field investigation found operation of a *86K10-1* lock-out relay tripped by protective relay *K10-51G*. *K10-51G* is a ground over-current relay located in the neutral circuit of the 6900V tertiary winding of Transformer *K10*. During this loss of *K10*, a smoke detector activated in the 10x10 Drive Complex.

The protective relay is a GE IAC53 electro-mechanical device. Besides a trip target, no other information is available when the relay operates. Since the relay had never had a previous trip it was decided to test the insulation of 6.9kV system. Insulation resistance tests found a failed 6.9kV cable on the tertiary winding feeding 10 x 10 SWT secondary drive motor #3 switchgear. Refer to Figure 2 for location of the failed cable.

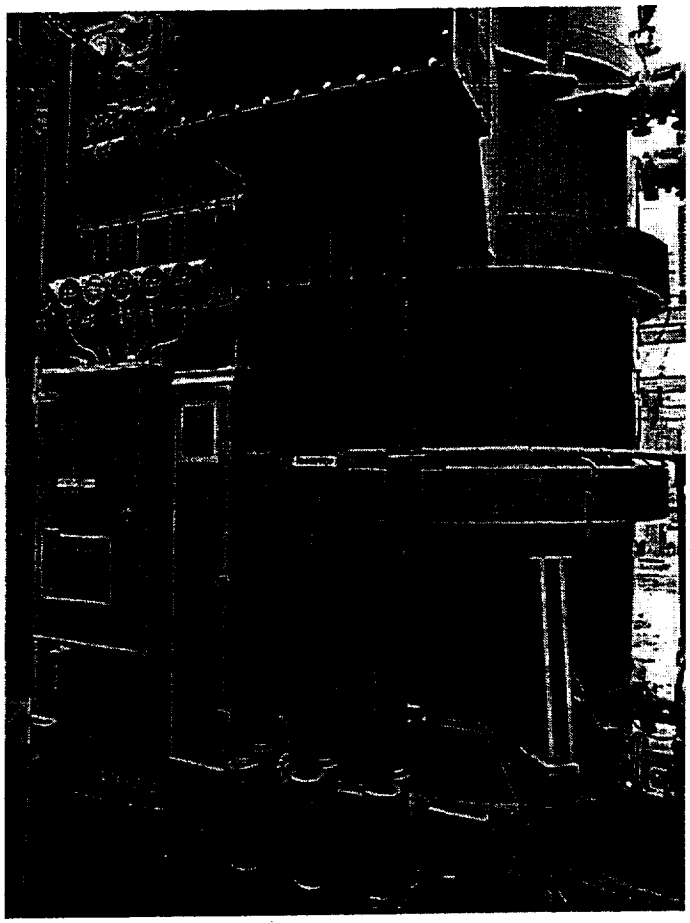

FIGURE 2 – XFMR *K10* FAILED 6.9kV CABLE

The failed cable has a conductor size of 2500kcmil copper. The only available replacement was a 35kV 2500kcmil cable manufactured by Okonite Corporation. Okonite will install a metal armor jacket on the cable for NASA's application. See Figure 3 for a vendor cut-sheet view of the new cable. The failed cable will be replaced during April 2002.

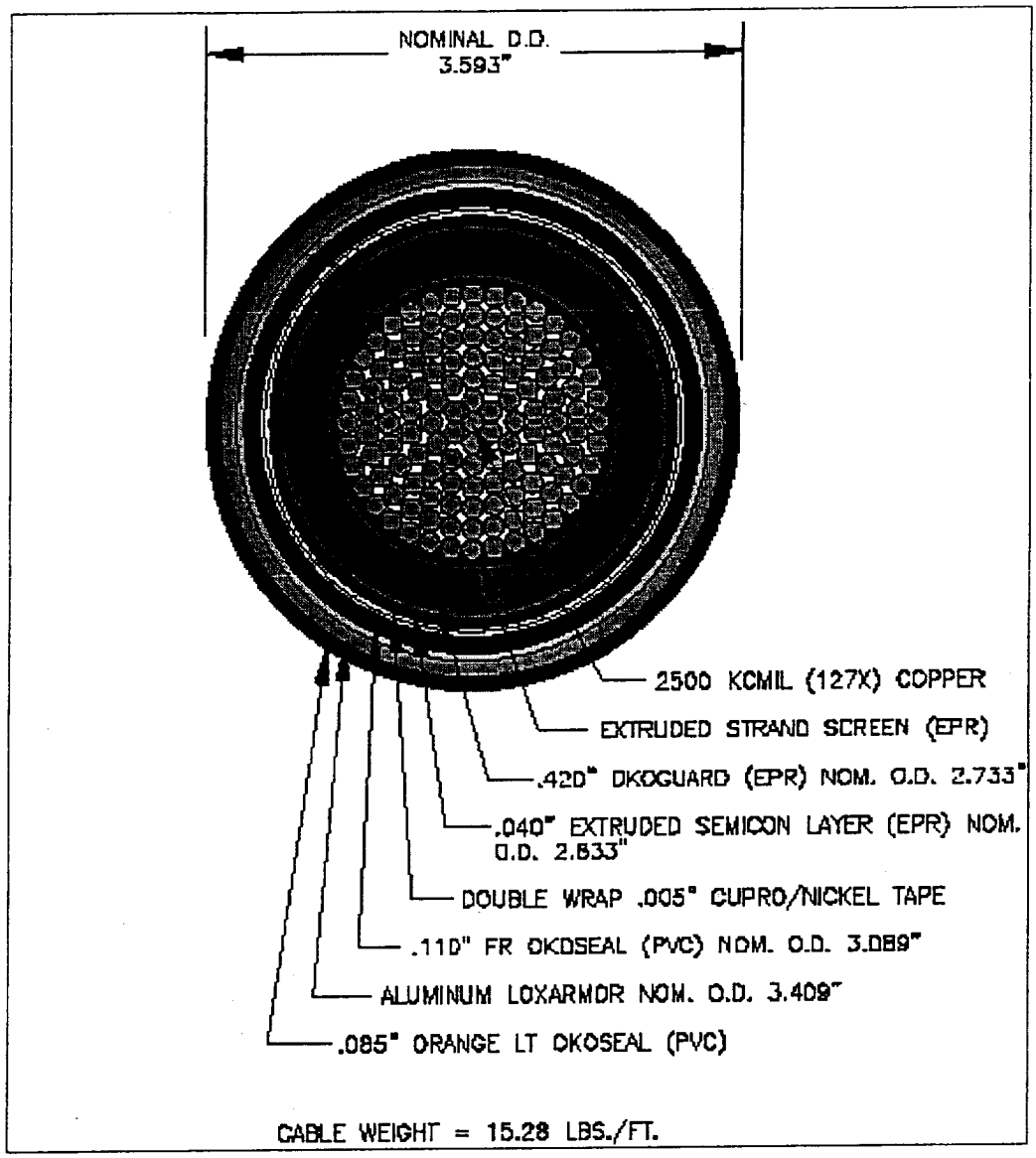

FIGURE 3 – XFMR *K10* REPLACEMENT 6.9kV CABLE

PROBLEM ON FIRST ENERGY'S *Q18* 138kV CIRCUIT

On 01/04/2002 during IST work on 138kV line *QA8B1* at Substation *A*, it was noted that the RFL9300 line current differential relay fault detector (FD) was picked up on 138kV circuit *QA10D1*, but the line was not tripped. The FD was for a ground, and no phase FD's were picked up. The same was true for the Substation *K* RFL9300. The ground FD pick-up is 0.5A. Phase FD pick-up is 6.0A. Since the RFL9300 had not tripped and a ground FD was picked-up at both substations, it was determined that the ground problem was not on circuit *QA10D1*.

The following switching was done in the field to isolate the system problem (Refer to Figure 4 for a simplified relay 1L):

- Open CS *K10PD*, while leaving *K6PD* closed. The FD at both Substation *A* and *K* cleared.
- Open CS *K6PD*.

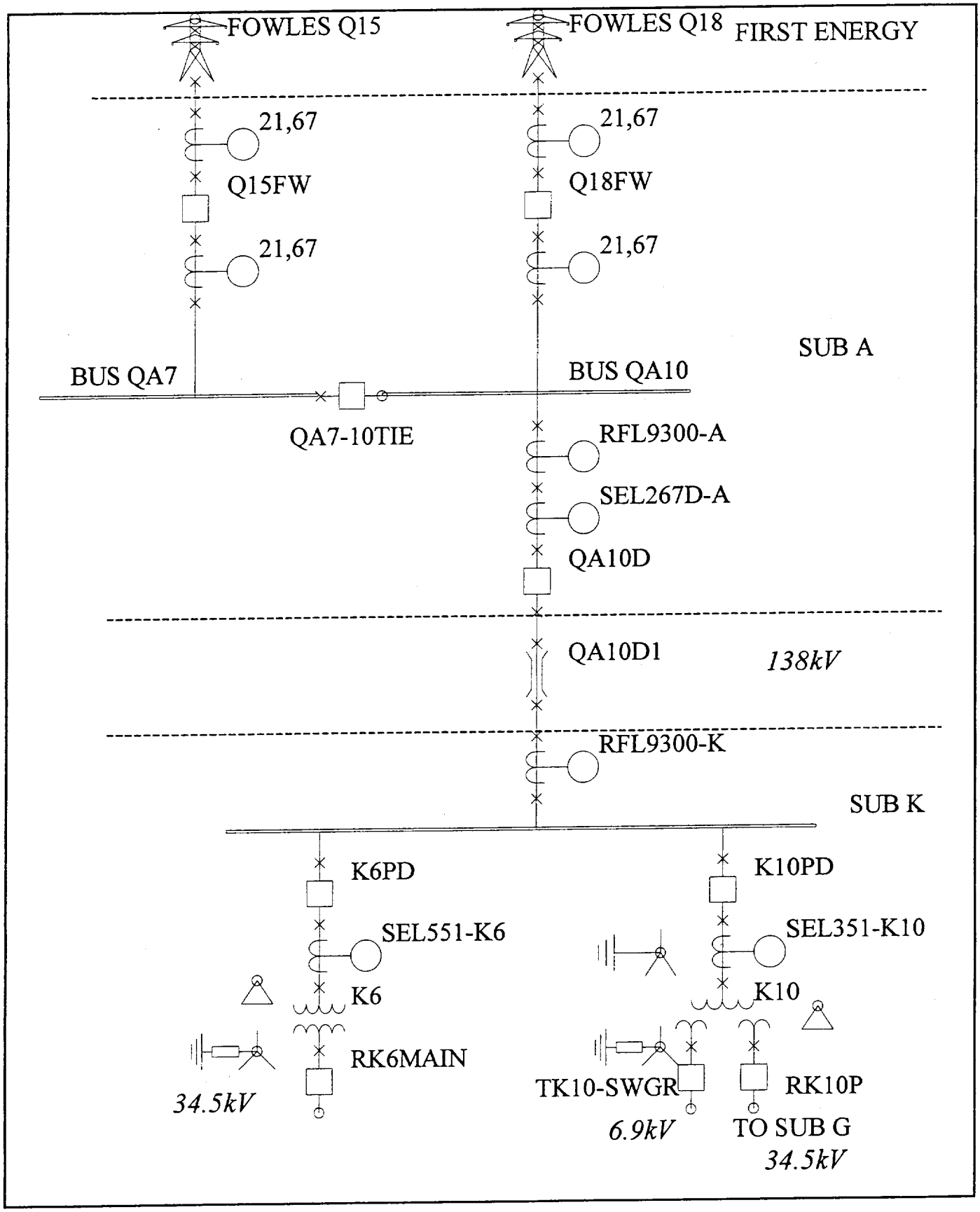

FIGURE 4 – SUBSTATION *A* – *K* SIMPLIFIED RELAY 1L DIAGRAM

- Remove all load from XFMR *K10* and close CS *K10PD*. The ground FD activated again. XFMR *K10* being fed from breaker *Q18FW*.
- Open CS *K10PD* and breaker *Q18FW*.
- Close CS *Q7-10TIE*.
- Close CS *K10PD* energizing *K10* from *Q15FW* via the *QA7-10TIE*. The ground FD did not activate.

This indicated that the system problem was located somewhere on the First Energy utility system. Electric Power Dispatch made several calls to First Energy regarding this. Initially, First Energy thought there was a CT problem on their circuit. However, even after this problem was repaired, NASA continued to get a FD on the *QA10D1* RFL9300. Data was collected from various relays and sent to First Energy. Condensed results appear in the Tables 1 - 6. Raw data appears in Appendix A. All data taken with *K6PD* open, *K10PD* closed, and no load on XFMR *K10*.

TABLE 1

XFMR *K10* fed from *Q18FW*						01/07/2002		
SEL351 @ Sub *K*, XFMR *K10*						RFL9300 FD Active		
	A	B	C	N	G	I1	3I2	3IO
I-mag	29	33	34	97	96	2.6	1.8	96
I-ang	0	2.6	-3.6	179	-0.4	-176	140	-.4

TABLE 2

XFMR *K10* fed from *Q18FW*						01/08/2002		
SEL351 @ Sub *K*, XFMR *K10*						RFL9300 FD Active		
	A	B	C	N	G	I1	3I2	3IO
I-mag	11	16	16	43	42	2.8	2.2	42
I-ang	0	-2	-17	172	-7.2	158	104	-7.2

TABLE 3

XFMR *K10* fed from *Q15FW* via *QA7-10TIE*						01/08/2002		
SEL351 @ Sub *K*, XFMR *K10*						RFL9300 FD Inactive		
	A	B	C	N	G	I1	3I2	3IO
I-mag	0.4	4	4.3	8.9	7.4	2.4	1.4	7.4
I-ang	0	-137	175	11.8	-160	19.3	3.6	-160

TABLE 4

XFMR *K10* fed from *Q18FW*				01/08/2002
RFL9300 @ Sub K – local; Sub A – remote				FD Active
	A	B	C	3IO
Local (Sub *K*)	0.0	0.0	0.0	0.5
Remote (Sub *A*)	0.0	0.0	0.0	0.5

TABLE 5				
XFMR *K10* fed from *Q15FW* via *QA7-10TIE* 01/08/2002				
RFL9300 @ Sub K – local; Sub A – remote FD Inactive				
	A	B	C	3IO
Local (Sub *K*)	0.0	0.0	0.0	0.0
Remote (Sub *A*)	0.0	0.0	0.0	0.0

TABLE 6			
XFMR *K10* fed from *Q18FW* 01/07/2002			
K10 Ground Relays		RFL9300 FD Active	
Device	Sec A	CT Ratio	Pri A
138kV GH1	1.2	400/5	96A
138kV GH2	1.2	400/5	96A
6.9kV G1	0.0	400/5	0A
6.9kV G2	0.0	400/5	0A

The following is observed with *Q18FW* feeding XFMR *K10*:

1. Tables 1 & 2 – Phase A, B, and C currents are similar in magnitude and very high for an unloaded XFMR (33A ~ 8MW at 138kV).
2. Tables 1 & 2 – Phase A, B, and C currents are in phase.
3. Tables 1 & 2 – N, G, & $3I_0$ current magnitude is summation of the three phase currents and very high.
4. Tables 1 & 2 – N is 180° out of phase with phase A reference current.
5. Tables 1 & 2 – G is in phase with phase A reference current.
6. Table 6 – Nearly 100A is flowing through the neutral H_0 bushing of XFMR *K10*.

The following is observed with *Q15FW* feeding XFMR *K10*:

1. Table 3 – Phase A, B, and C currents are close in magnitude and magnitude is small.
2. Table 3 – Phase A, B, and C currents though not 120° apart, do show phase angle separation.
3. Table 3 – N, G, & 3I currents magnitudes are small.
4. Table 3 – N is nearly in phase with phase A reference current.
5. Table 3 – G is nearly 180° out of phase with phase A reference current.

Also with *Q18FW* feeding Transformer *K10*, MW readings at Electric Power Dispatch for the metered lab load were 8-10MW higher than calculated expected load. With *Q18FW* opened, expected and metered lab loads closely matched.

On 01/08/2002 First Energy contacted NASA to state that they had found a problem with a failed vacuum bottle, one phase only, on a 138kV circuit switcher to Ford Motor Company on circuit *Q18*. No further details were provided regarding this failure. The failure resulted in circulating currents on the 138kV line. First Energy and Ford were both unaware they had a problem on the power system. The vacuum bottle was replaced and circuit *Q18* returned to service. No further problems, RFL9300 FD operation, or unusual currents occurred with *Q18FW* feeding Transformer *K10*.

FAILURE OF *QA10D1* 138kV CABLE – PHASE A

On 01/19/2002 at approximately 21:50, 138kV circuit *QA10D1* tripped off-line with the following breakers opening (Refer to Figure 4):

- *QA10D*
- *K6PD*
- *K10PD*
- *RK6MAIN*

All breakers had a white light, indicating a relay trip. The following relay targets were found:

- Sub *A* – *QA10D1* RFL9300: • Trip 1, • A-G Fault
- Sub *K* – *QA10D1* RFL9300: • Trip 1 & 2, • A-G Fault
- Sub *K* – XFMR *K6* SEL551: • A Instantaneous Fault

Relay event data was downloaded for all the relays associated with *QA10D1* line. Event plots and phasor diagrams appear in Figures 5 – 12. From this data, it was obvious that a fault had occurred on *QA10D1* and was most likely a single phase-to-ground fault on phase A.

The deep tunnel between Subs *A* and *K* was entered by high voltage personnel and a fault was found on phase A of *QA10D1* near the Sub *A* end of the line. See Figures 13 and 14.

The *QA10D1* phase-A cable is 500kcmil cross-linked polyethylene (XLPE). Phases B and C of this circuit are oil-paper-lead insulated. It appears that the phase A XLPE cable had failed previously (~1968) due to the location of two splices near the failed section.

A spare section of 500kcmil XLPE is located in the deep tunnel. The failed section of *QA10D1* phase-A cable, including the section spliced in 1968 is to be replaced in April 2002

SUMMARY

1. Repair/replacement of high voltage cables at Glenn have had a significant effect on budgets and down time.
2. However, high voltage cables are less expensive and have relatively short lead time when compared to transformers and breakers.
3. Installation of micro-processor based relays have improved reliability and field engineering of Glenn power system.

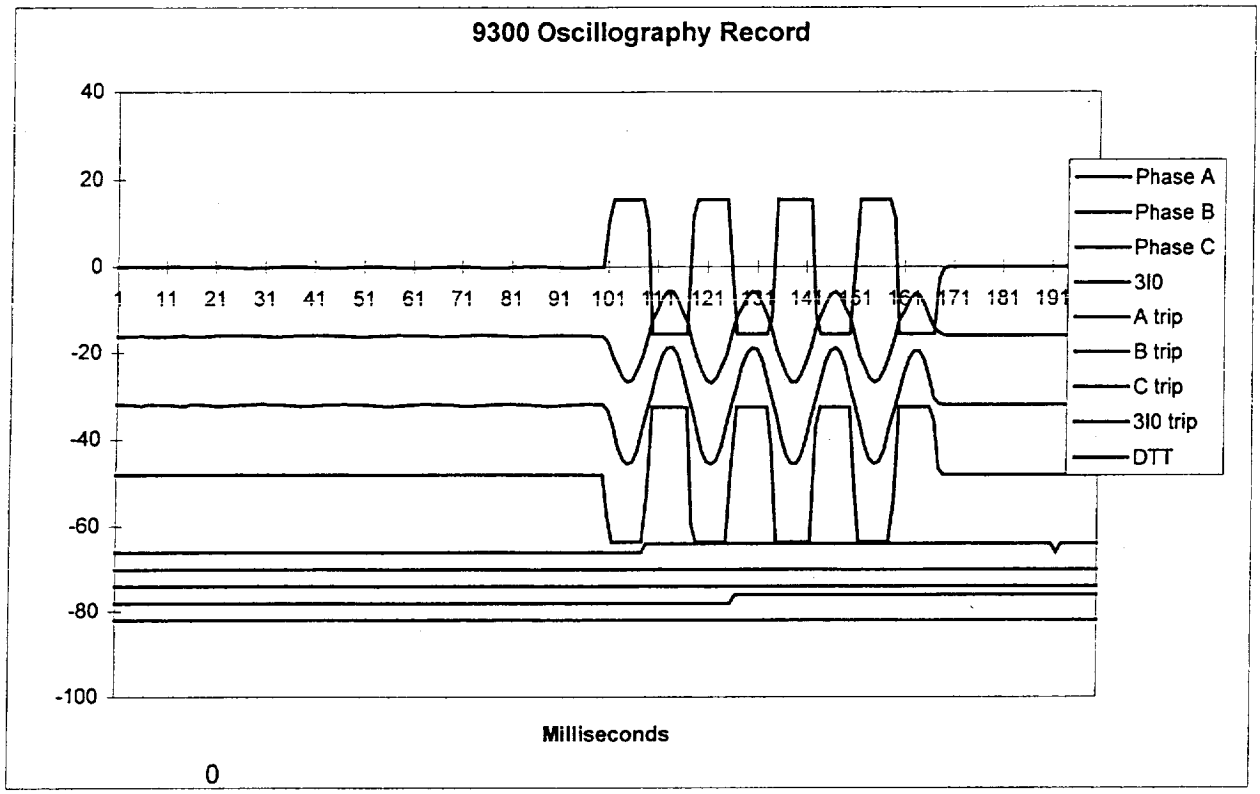

Figure 5 – Substation *A* – RFL9300 Event Plot for *QA10D1* PH-A Fault

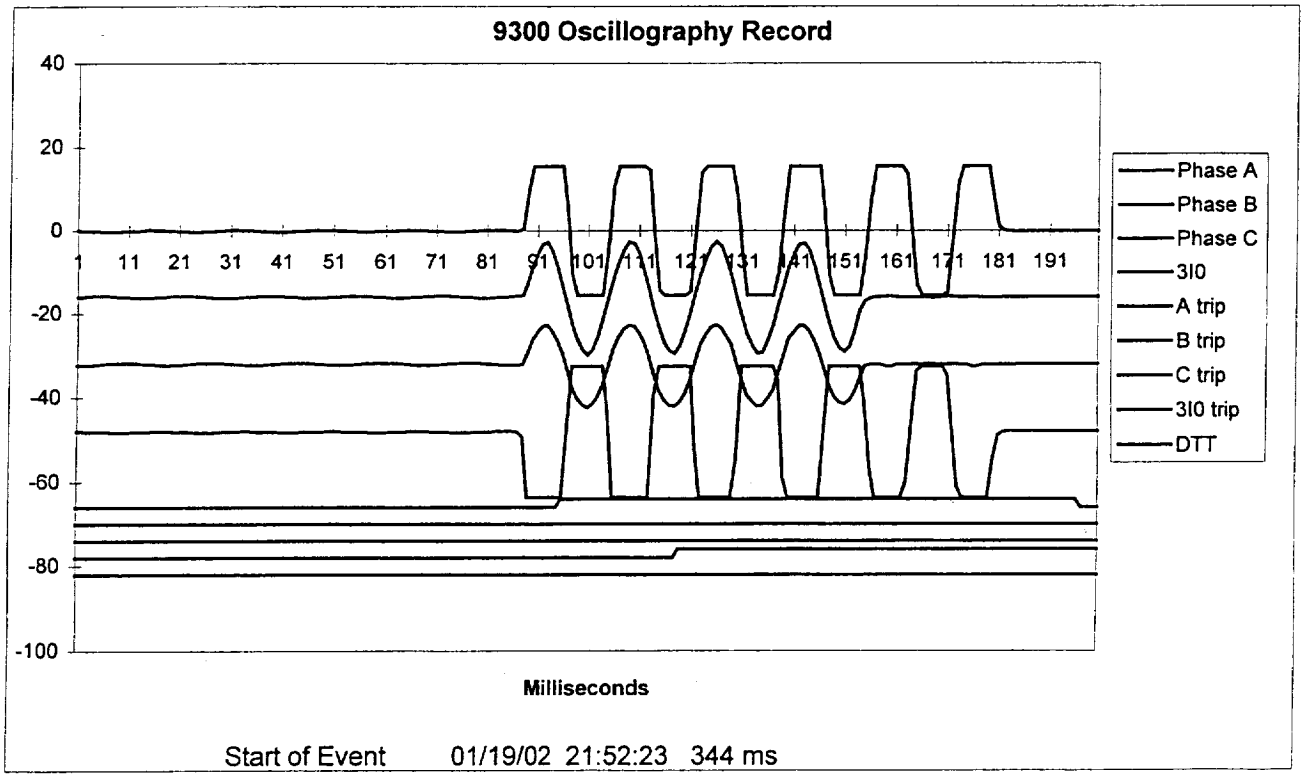

Figure 6 – Substation *K* – RFL9300 Event Plot for *QA10D1* PH-A Fault

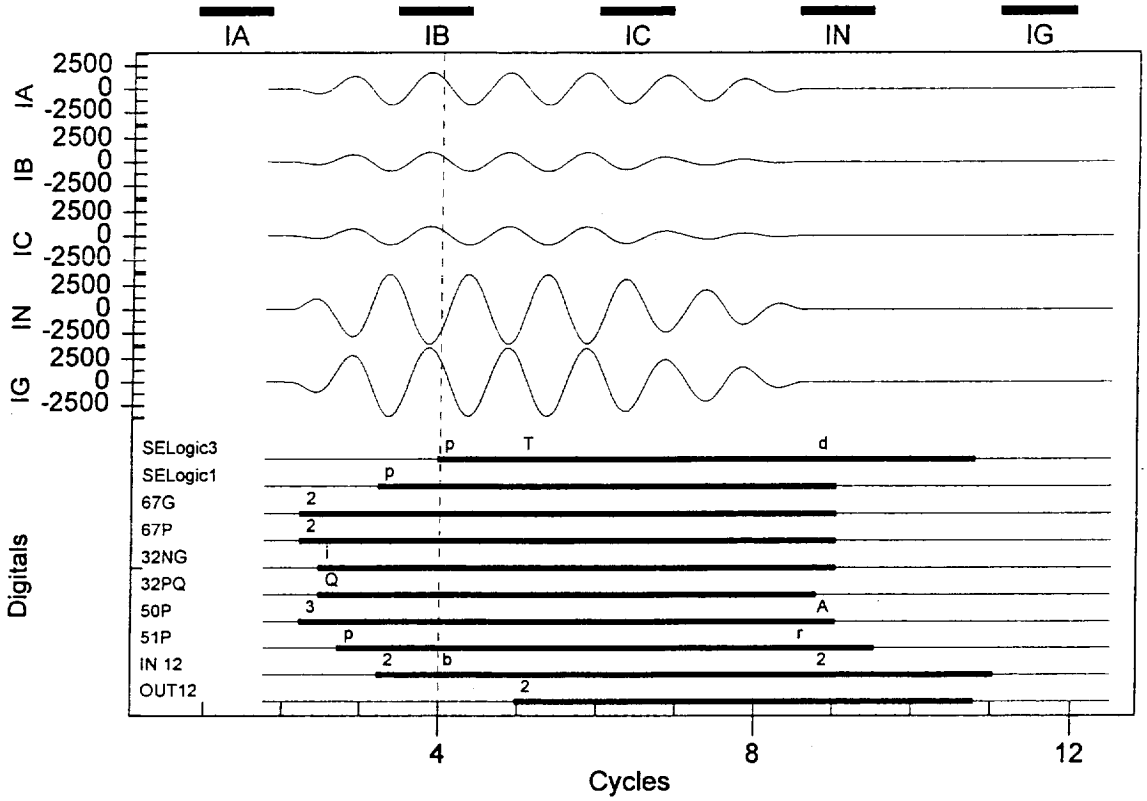

Figure 7 – XFMR *K10* SEL351 Event Plot for *QA10D1* PH-A Fault

Dashed line at 4-cycles represents snapshot location for Phasor Diagrams plots in Figures 8 & 9.

Digital Channel Descriptions:

- SELogic3 – Line Protection = (IN102 + SV1) * (50P2 + G0G2)
- SELogic1 – Breaker Failure = IN101 * !(50P1 + 67G1)
- 67G – Residual Ground Instantaneous Element w/directional control
- 67P – Phase Instantaneous Element w/directional control
- 32NG – Channel IN Current-Polarized for Element for Neutral & Residual Ground OC
- 32PQ – Negative-Sequence Voltage-Polarized Element for Phase OC
- 50P – Phase Instantaneous Element
- 51P – Phase Time-OC Element
- IN1 – IN101 – RFL9745 Trip Received
- IN2 – IN102 – BFI Received
- OUT1 = OUT101 = TRIP = 51PT + 51GT + 67G1T
- OUT2 = OUT102 = SV3T

Digital Plot Symbols

- 1 – OUT1 or IN1 asserted
- 2 – OUT1 or IN2 asserted
- b – Both OUT1 & 2 or IN1 & 2 asserted
- p – element or SELogic picked up
- T – element tripped or SELogic timed out
- d – SELogic asserted while timer timing on dropout time
- r – element timing to reset
- 3 – element 50P A, B, & C picked up
- A – element 50P single-phase 50A picked up
- i – Reverse channel IN current-polarized directional element picked up
- Q – Reverse negative-sequence directional element picked up
- 2 – Level 2 67G or 67P instantaneous element 2 picked up; Level 1 not picked up

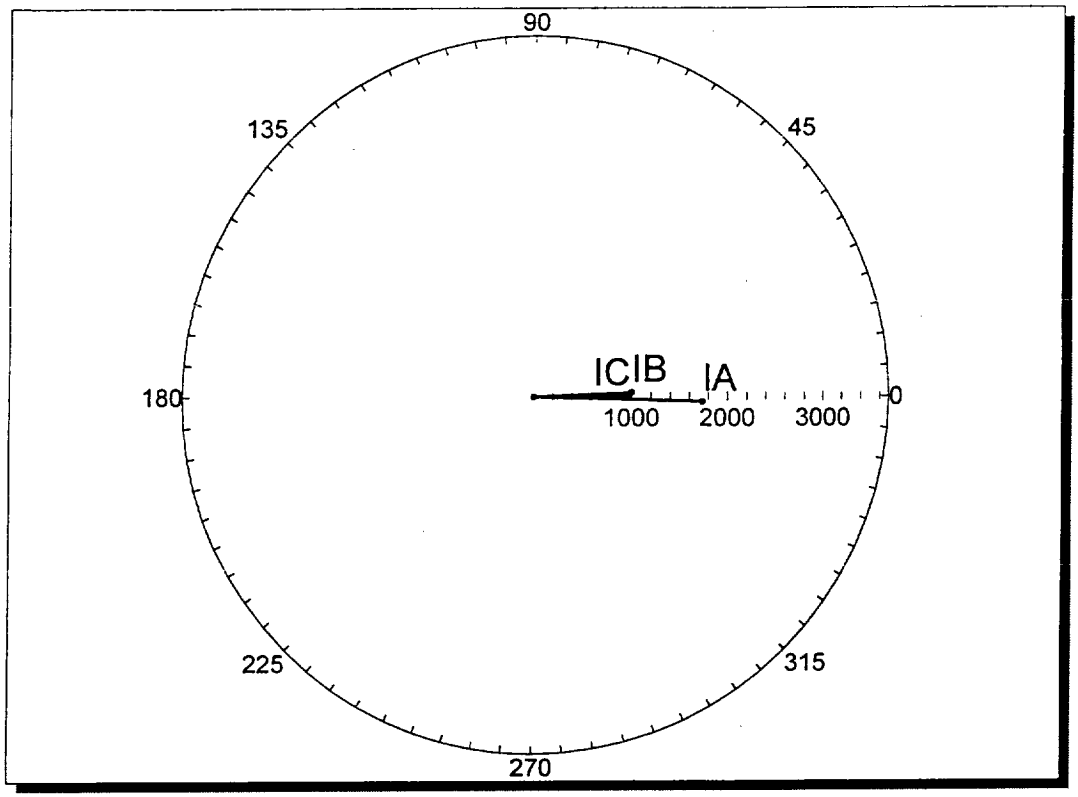

Figure 8 – XFMR *K10* SEL351 Phasor Plot for *QA10D1* PH-A Fault Phase Currents (snapshot at 4 cycles)

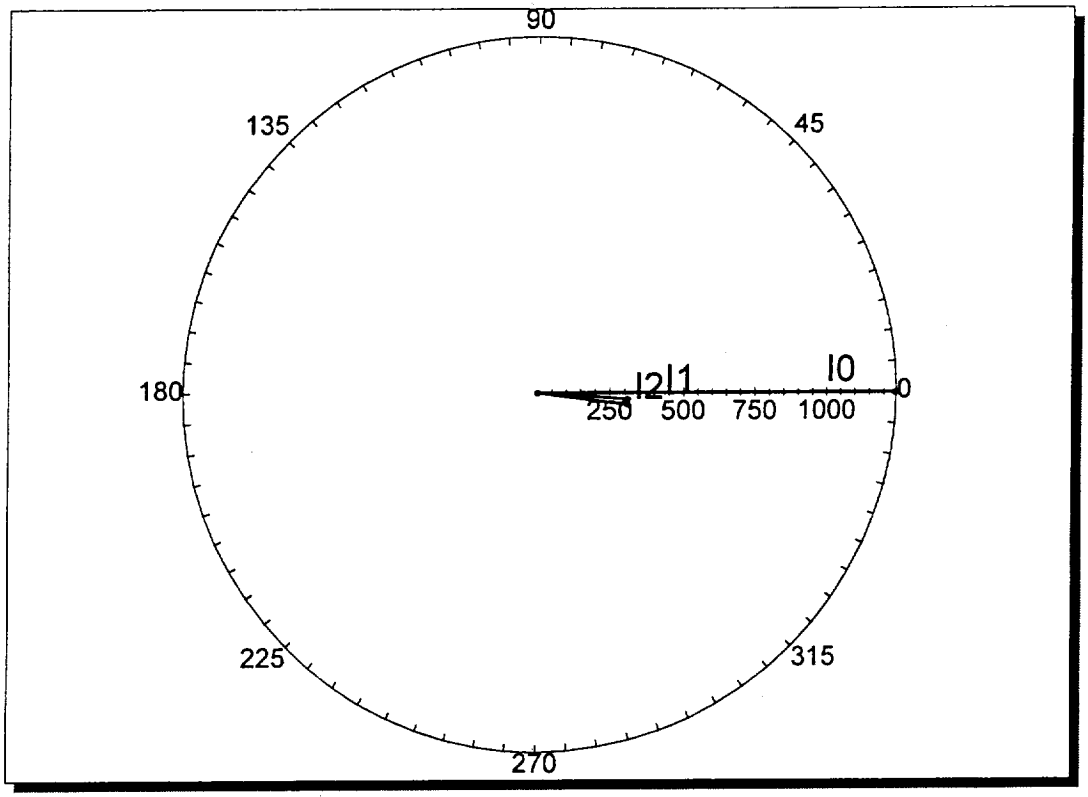

Figure 9 – XFMR *K10* SEL351 Phasor Plot for *QA10D1* PH-A Fault Sequence Components (snapshot at 4 cycles)

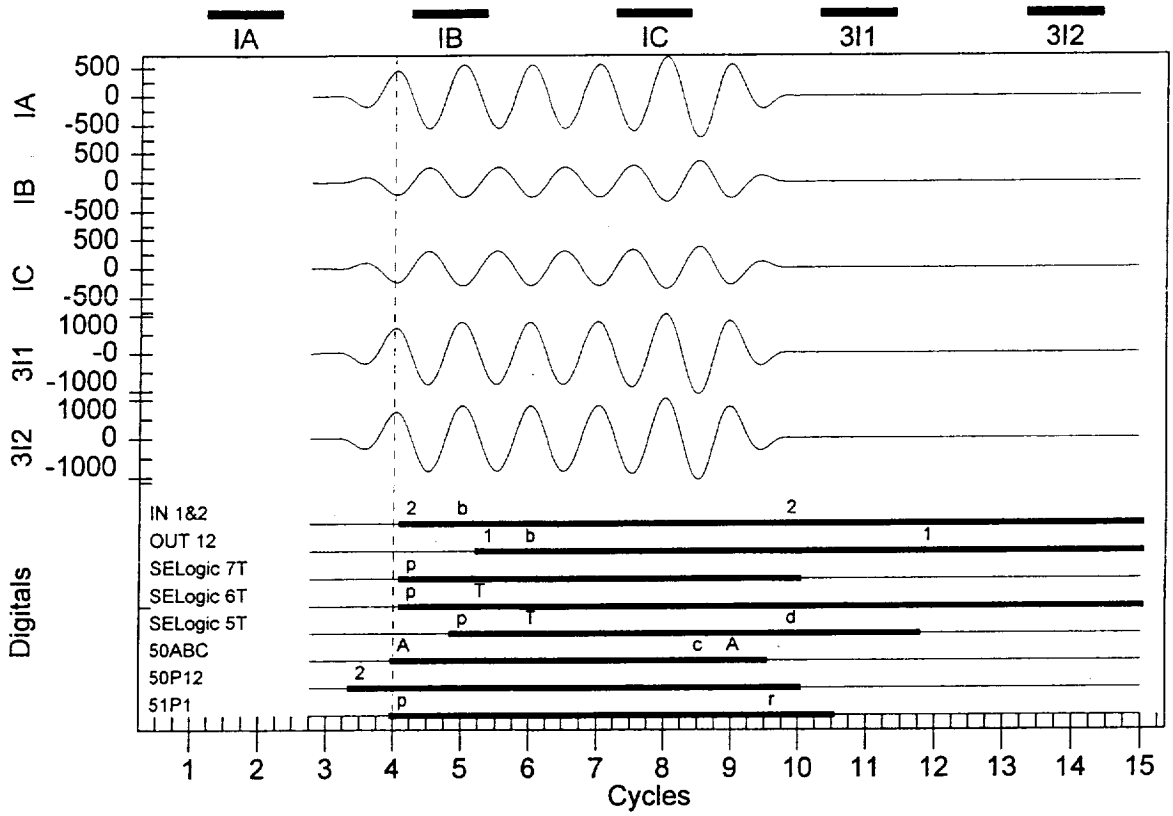

Figure 10 – XFMR *K6* SEL551 Event Plot for *QA10D1* PH-A Fault

Dashed line at 4-cycles represents snapshot location for Phasor Diagrams plots in Figures 11 & 12.

Digital Channel Descriptions:

- IN1 – RFL9745 Trip Received
- IN2 – BFI Received
- OUT1 = TRIP = 50P1 + 50N1 + 51P1T + 51N1T + SV6T
- OUT2 = SV5T
- SELogic 7T – Breaker Failure = (IN2 + SV5) * (50P2 + 50N2)
- SELogic 6T – Retrip Function = IN2
- SELogic 5T – Line Protection = IN1 * !(50P1 + 50N1)
- 50ABC – Single Phase Instantaneous Elements
- 50P12 – Phase Instantaneous Element
- 51P1 – Phase Time-OC Element

Digital Plot Symbols

- 1 – OUT1 or IN1 asserted
- 2 – OUT2 or IN2 asserted
- b – Both OUT1 & 2 or IN1 & 2 asserted
- p – element or SELogic picked up
- T – element tripped or SELogic timed out
- d – SELogic asserted while timer timing on dropout time
- r – element timing to reset
- A – element 50P single-phase 50A picked up
- c – element 50P phases A & C picked up
- 2 – phase instantaneous element 50P2 picked up

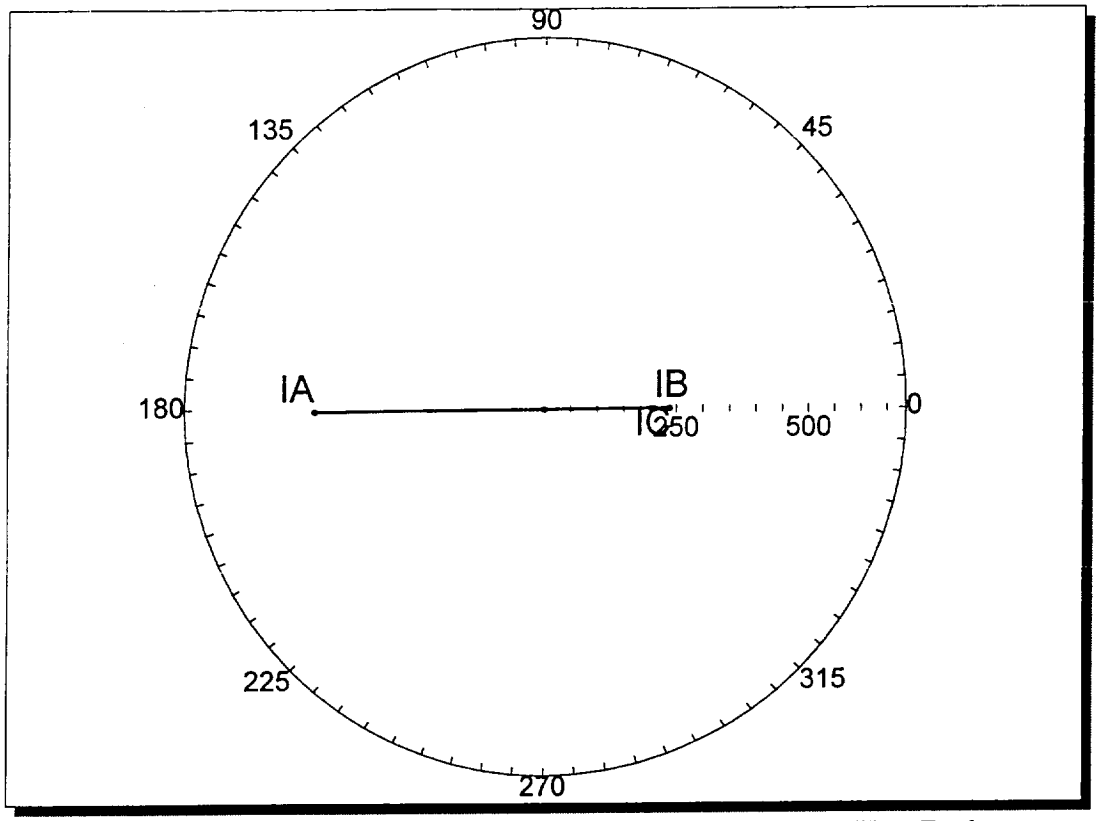

Figure 11 – XFMR *K6* SEL551 Phasor Plot for *QA10D1* PH-A Fault Phase Currents (snapshot at 4 cycles)

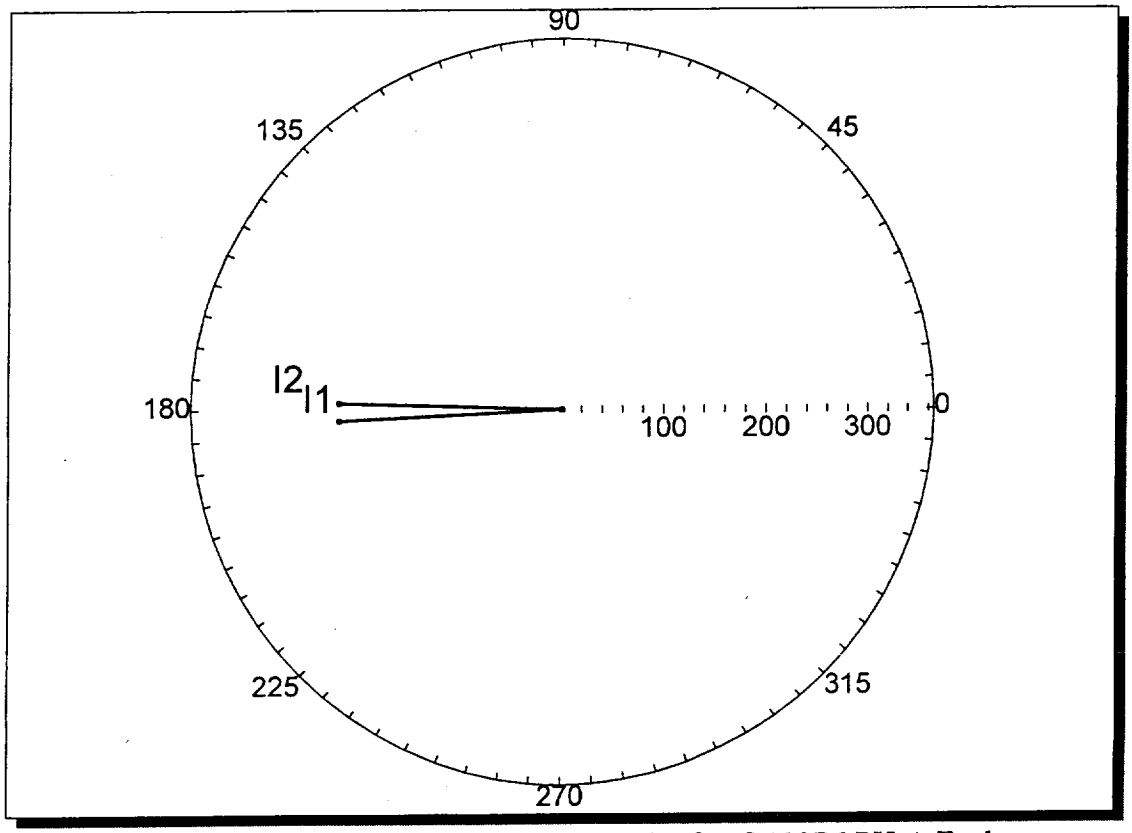

Figure 12 – XFMR *K6* SEL551 Phasor Plot for *QA10D1* PH-A Fault Sequence Components (snapshot at 4 cycles)

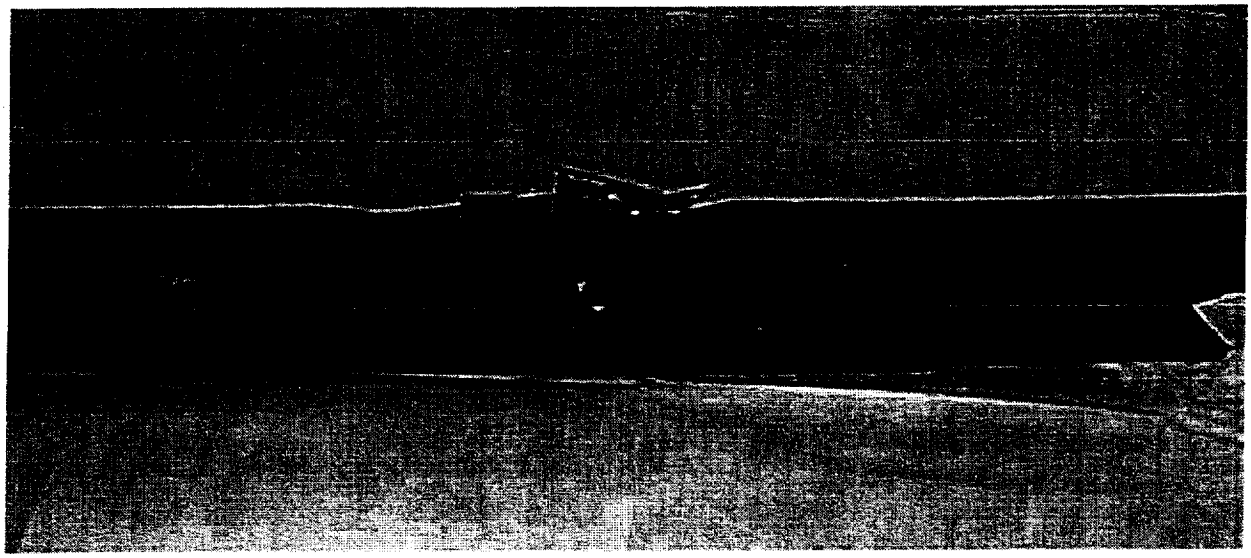

Figure 13 - Failed *QA10D1* Phase A 138kV Cable

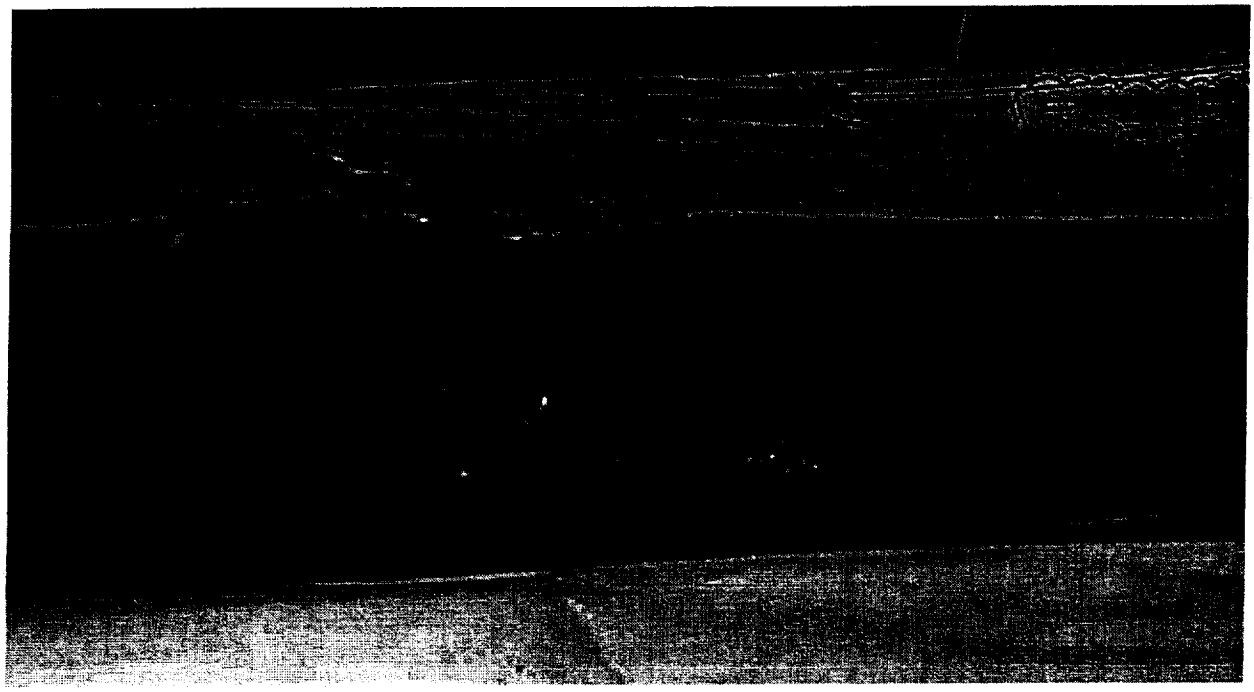

Figure 14 - Failed *QA10D1* Phase A 138kV Cable

APPENDIX A – RELAY FIELD DATA – FIRST ENERGY LINE PROBLEM

XFMR K10 SEL351 READINGS ON 01/07/2002
XFMR FED BY BRKR Q18FW AND NO LOAD ON XFMR

HIGH CURRENTS ON PHASE A,B,C, AND NEUTRAL
I PHASE ANGLE FOR A,B,C ALL NEARLY ZERO AND
NEUTRAL PHASE ANGLE 180 OUT; GROUND IS 0 OUT.

MET 11□ SEL-351 RELAY @ SUB K

TRANSFORMER K10 Date: 01/07/02 Time: 08:47:46.517
CS QK10L

	A	B	C	N	G
I MAG (A)	29.082	33.157	34.200	97.374	96.339
I ANG (DEG)	0.00	2.61	-3.57	179.02	-0.37

	I1	3I2	3I0	V1	V2	3V0
MAG	2.572	1.832	96.339	0.000	0.000	0.000
ANG (DEG)	-175.81	139.63	-0.37	-112.99	-46.00	-133.83

TRANSFORMER K10 Date: 01/07/02 Time: 08:47:51.766
CS QK10L

	A	B	C	N	G
I MAG (A)	28.971	32.993	34.121	97.004	95.983
I ANG (DEG)	0.00	2.50	-3.78	179.03	-0.48

	I1	3I2	3I0	V1	V2	3V0
MAG	2.582	1.898	95.983	0.000	0.000	0.000
ANG (DEG)	-176.04	134.92	-0.48	-72.93	-68.06	-145.71

TRANSFORMER K10 Date: 01/07/02 Time: 08:47:57.017
CS QK10L

	A	B	C	N	G
I MAG (A)	29.285	33.284	34.355	97.848	96.823
I ANG (DEG)	0.00	2.58	-3.67	179.05	-0.42

	I1	3I2	3I0	V1	V2	3V0
MAG	2.568	1.789	96.823	0.000	0.000	0.000
ANG (DEG)	-175.95	135.76	-0.42	-75.79	-41.07	-175.03

XFMR K10 SEL351 READINGS ON 01/08/2002
XFMR FED BY BRKR Q18FW AND NO LOAD ON XFMR

HIGH CURRENTS ON PHASE A,B,C, AND NEUTRAL
I PHASE ANGLE FOR A,B,C ALL NEARLY ZERO AND
NEUTRAL PHASE ANGLE 180 OUT; GROUND IS 0 OUT.

TRANSFORMER K10 Date: 01/08/02 Time: 08:52:09.776
CS QK10L

	A	B	C	N	G
I MAG (A)	11.124	15.581	15.696	42.920	41.997
I ANG (DEG)	0.00	-2.05	-17.51	171.48	-7.22

	I1	3I2	3I0	V1	V2	3V0
MAG	2.791	2.186	41.997	0.000	0.000	0.000
ANG (DEG)	157.81	104.28	-7.22	-69.10	-71.33	112.91

TRANSFORMER K10 Date: 01/08/02 Time: 08:52:15.151
CS QK10L

	A	B	C	N	G
I MAG (A)	11.182	15.602	15.680	43.093	42.060
I ANG (DEG)	0.00	-1.95	-17.44	171.52	-7.14

	I1	3I2	3I0	V1	V2	3V0
MAG	2.776	2.121	42.060	0.000	0.000	0.000
ANG (DEG)	157.68	103.20	-7.14	-112.78	-126.68	41.09

FREQ (Hz) 60.00 VDC (V) 130.3□□

TRANSFORMER K10 Date: 01/08/02 Time: 08:52:20.898
CS QK10L

	A	B	C	N	G
I MAG (A)	11.204	15.618	15.663	43.085	42.083
I ANG (DEG)	0.00	-1.80	-17.34	171.63	-7.04

	I1	3I2	3I0	V1	V2	3V0
MAG	2.772	2.059	42.083	0.000	0.000	0.000
ANG (DEG)	157.74	102.87	-7.04	-66.34	-104.90	148.09

XFMR K10 SEL351 READINGS ON 01/08/2002
XFMR FED BY BRKR Q15FW VIA QA7-10TIE W/Q18FW OPEN - NO LOAD ON XFMR

LOW CURRENTS ON PHASE A,B,C, AND NEUTRAL
I PHASE ANGLE FOR A,B,C ~120-DEGREES APART
NEUTRAL PHASE ANGLE 0, GROUND PHASE ANGLE ~180 OUT.

MET 10□

TRANSFORMER K10 Date: 01/08/02 Time: 09:51:08.586
CS QK10L

	A	B	C	N	G
I MAG (A)	0.386	4.093	4.348	8.853	7.396
I ANG (DEG)	0.00	-137.80	175.88	11.80	-160.76

	I1	3I2	3I0	V1	V2	3V0
MAG	2.373	1.421	7.396	0.000	0.000	0.000
ANG (DEG)	19.26	3.59	-160.76	-128.55	-92.78	-42.99

FREQ (Hz) 60.00 VDC (V) 130.3□□

TRANSFORMER K10 Date: 01/08/02 Time: 09:51:13.711
CS QK10L

	A	B	C	N	G
I MAG (A)	0.347	4.063	4.328	8.976	7.375
I ANG (DEG)	0.00	-128.74	-176.16	20.02	-152.03

	I1	3I2	3I0	V1	V2	3V0
MAG	2.357	1.298	7.375	0.000	0.000	0.000
ANG (DEG)	27.52	8.49	-152.03	-125.71	-144.52	20.81

TRANSFORMER K10 Date: 01/08/02 Time: 09:51:19.212
CS QK10L

	A	B	C	N	G
I MAG (A)	0.289	4.092	4.331	9.001	7.483
I ANG (DEG)	0.00	-139.62	174.56	10.28	-162.58

7

READINGS TAKEN WITH AMP-PROBE IN BUILDING 90 01/07/02 TIME ~09:00:00
138kV NEUTRAL GH1 RELAY = 1.2A GE-IAC51 TAP = 4A CT = 600/5
138kV NEUTRAL GH2 RELAY = 1.2A GE-IAC51 TAP = 4A CT = 600/5
6.9kV NEUTRAL G1 RELAY = 0A GE-IAC53 TAP = 2.5A
6.9kV NEUTRAL G2 RELAY = 0A GE-IAC53 TAP = 2.5A
138/34.5/6.9/6.9kV 87T RELAY TERMINALS 3,4,5,6 = 0A GE-STD

XFMR K10 RFL9300 READINGS ON 01/08/2002
XFMR FED BY LINE Q18FW AND NO LOAD ON XFMR

3I0 READINGS .5A AT BOTH LOCAL (SUB K) AND REMOTE (SUB A) SITES

#	DESCRIPTION	VALUE
001	Ping Pong R1	004.0 ms
003	CDC Remote #1	004.0 ms
005	Local I A	00.00 Amps
006	Local I B	00.00 Amps
007	Local I C	00.00 Amps
008	**Local 3I0**	**00.50 Amps**
009	Remote #1 I A	00.00 Amps
010	Remote #1 I B	00.00 Amps
011	Remote #1 I C	00.00 Amps
012	**Remote #1 3I0**	**00.50 Amps**
017	Remote Address 1	Tx Addr Verified

9300>

ALL OTHER READINGS WITH Q18FW OPEN WERE 0.00 Amps